

# Final Technical Report for NAG 5 3819

June, 1998

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This NASA grant has funded studies of cosmic objects observed by both the EGRET detector aboard the Compton Gamma-ray Observatory and Whipple Gamma-ray imaging telescope. The former has sensitivity up to a few GeV and latter has sensitivity starting at about 200 GeV extending up to beyond 10 TeV. Thus these instruments probe some of the most energetic phenomena in the universe. This program has been in place for several years and led to important results referred to below.

The Whipple Observatory Imaging Cherenkov Telescope consists of a 10-meter reflector with a nanosecond photomultiplier-tube camera at the focal plane. During the time period covered by this grant, it had 151 pixels or 331 pixels on a 1/4 degree hexagonal pattern. As a TeV gamma ray enters the atmosphere, it produces an electron/positron pair initiating an extensive air shower. Cherenkov light from the electrons and positrons in the shower form an image of the shower at the phototube camera. The shape and intensity of this image is used to distinguish gamma-ray initiated showers from cosmic-ray (largely proton and alpha-particle) background showers and to derive an energy estimate for the primary gamma-ray. The Whipple Observatory gamma-ray collaboration pioneered this imaging technique which normally rejects over 99 percent of the cosmic-ray background while keeping over 70 percent of the gamma-ray signal. One of its key features is large collection area which can exceed 50,000 meters<sup>2</sup>.

This grant covered two major efforts. The first was correlated observations of Markarian 421 and Markarian 501, the two known TeV AGN's. These objects were observed with the Whipple gamma-ray telescope when possible and, because of the high flux detected from Markarian 501 (Breslin, A., et al. 1997, IAUC, 6241), a ToO for CGRO which we had requested was granted in April 1997. This led to the OSSE detection of up to 400 keV photons from Markarian 501 and an EGRET upper limit which indicates a rapid drop-off in power output between EGRET and Whipple energies. BATSE observations of the two AGNS were analyzed by Dick Lamb and no evidence for flares was seen. The results are given in Catanese et al., 1998 and Samuelson et al., 1998 (see below). The second major effort consisted of observations of all northern hemisphere BL Lac objects on the Einstein Slew Survey which have redshifts of less than 0.2. These observations were made, but with no new detections. The results were given in two conference proceedings: Catanese, M., et al. 1997, Proc. of the Fourth Compton Symposium, Williamsburg, VA, eds.

C.D. Dermer, M.S. Strickman, J.D. Kurfess, AIP:New York, 1397 and Catanese, M., et al. 1997, Proc. of the 25th ICRC (Durban, South Africa), eds. M.S. Potgeier, B.C. Raubenheimer, D.J. van der Walt, 3, 277. The work is now being written up for publication as a journal article. The money from this grant was used to partially support two post-docs, Mike Catanese and Frank Krennrich.

Among the recent accomplishments of the Whipple Observatory relevant for work in this area and which have been partially underwritten by this and other recent NASA ISU grants are: (1) Discovery of a flare from Markarian 421 (paper by Kerrick et al. 1995 below). (2) Multiwavelength observations of Markarian 421 during this same flare (paper by Macomb et al. 1995). (3) Discovery of a second TeV AGN, Markarian 501 (paper by Quinn et al. 1996). (4) Observation of Markarian 421 at large zenith angles (paper by Krennrich et al., 1997). (5) Discovery of a third TeV AGN (paper by Catanese et al., 1997). (6) Discovery of remarkably intense and short flares from Markarian 421 (paper by Gaidos et al., 1996) and (7) measured the spectrum during this flare (Zweerink et al., 1997). (8) Organization of multi-wavelength campaigns for observation of Markarian 421 (see., e.g. Buckley et al., 1996) and Markarian 501 (Catanese et al., 1997). (9) Setting TeV emission limits for several shell-type supernova remnants which are putative sources for galactic cosmic-rays (Buckley et al., 1997).

Below we list refereed publications that have been supported, at least in part, by this grant and related recent ISU NASA grants.

### Refereed Publications

Kerrick, A.D., Akerlof, C., Biller, S.D., Buckley, J.H., Cawley, M.F., Chantell, M., Connaughton, V., Fegan, D.J., Fennell, S., Gaidos, J.A., Hillas, A.M., Lamb, R.C., Lewis, D.A., Meyer, D.I., McEnery, J., Mohanty, G., Quinn, J., Rovero, A.C., Rose, H.J., Schubnell, M.S., Sembroski, G., Urban, M., Watson, A.A., Weekes, T.C., West, M., Wilson, C., and Zweerink, J., "Outburst of TeV Photons from Markarian 421", *ApJL*, 438, L59, 1995.

Biller, S.D., Akerlof, C.W., Buckley, J., Cawley, M.F., Chantell, M., Fegan, D.J., Fennell, S., Gaidos, J.A., Hillas, A.M., Kerrick, A.D., Lamb, R.C., Lewis, D.A., Meyer, D.I., Mohanty, G., O'Flaherty, K.S., Punch, M., Reynolds, P.T., Rose, H.J., Rovero, A.C., Schubnell, M.S., Sembroski, G., Weekes, T.C., West, M., and Wilson, C., "An Upper Limit to the IR Background from Observations of TeV Gamma Rays" *ApJ*, 445, 227, 1995.

Krennrich, F. and R. C. Lamb, "Low Energy  $\gamma$ -ray Events in Imaging Cherenkov Telescope Arrays", *Exp. Astronomy*, 6, 285, 1995.

Lamb, R.C., "Overview of TeV Gamma Ray Observations", *Space Science Reviews*, 7512, 53, 1996.

Chantell, M., Akerlof, C.W., Badran, H., Buckley, J.H., Carter-Lewis, D.A., Cawley, M.F., Connaughton, V., Fegan, D.J., Fleury, P., Gaidos, J.A., Hillas, A.M., Lamb, R.C., Paré, E., Rose, H.J., Rovero, A.C., Sarazin, X., Sembroski, G., Schubnell, M.S., Urban, M., Weekes, T.C., Wilson, C., "A Hybrid Version of the Whipple Observatory's Air Cherenkov Imaging Camera for Use in Moonlight," *Astroparticle Phys.*, in press.

Krennrich, F., Akerlof, C.W., Biller, S.D., Burdett, A.M., Breslin, A.C., Buckley, J.H., Carter-Lewis, D.A., Cawley, M.F., Catanese, M., Connaughton, V., Fegan, D.J., Finley, J.P., Gaidos, J.A., Hillas, A.M., Lamb, R.C., Lessard, R., McEnery, J.E., Mohanty, G., Quinn, J., Rodgers, A.J., Rose, H.J., Schubnell, M.S., Sembroski, G., Weekes, T.C., Wilson, C., Zweerink, J., "Detection of Multi-TeV Emission from Markarian 421," *Astrophys. J.*, in press.

Quinn, J., Akerlof, C.W., Biller, S.D., Buckley, J.H., Carter-Lewis, D.A., Cawley, M.F., Catanese, M., Connaughton, V., Fegan, D.J., Finley, J.P., Gaidos, J.A., Hillas, A.M., Krennrich, F., Lamb, R.C., Lessard, R., McEnery, J., Meyer, D.I., Mohanty, G., Rodgers, A., Rose, H.J., Schubnell, M.S., Sembroski, G., Weekes, T.C., Wilson, C. and Zweerink, J., 1996, *ApJL* 456, L83. Detection of Gamma Rays with  $E > 300$  GeV from Markarian 501.

Kerrick, A. D., Akerlof, C. W., Biller, S. D., Buckley, J. H., Carter-Lewis, D.A., Cawley, M.F., Chantell, M., Connaughton, V., Fegan, D. J., Fennell, S., Gaidos, J. A., Hillas, A. M., Kwok, P. W., Lamb, R. C., Lappin, T., Lessard, R., Meyer, D. I., McEnery, J., Mohanty, G., Quinn, J., Rose, H. J., Rovero, A. C., Sembroski, G., Schubnell, M. S., Weekes, T. C., West, M., Wilson, C. and Zweerink, J., 1995, *ApJ*, 452, 588. Upper Limits on TeV Emission from Active Galactic Nuclei.

Macomb, D.J., Akerlof, C.W., Aller, H.D., Aller, M.F., Bertsch, D.L., Bruhweiler, F., Buckley, J.H., Carter-Lewis, D.A., Cawley, M.F., Cheng, K.P., Dermer, C., Fegan, D.J., Gaidos, J.A., Gear, W.K., Hall, C.R., Hartman, R.C., Hillas, A.M., Kafatos, M., Kerrick, A.D., Kniffen, D.A., Kondo, Y., Kubo, H., Lamb, R.C., Makino, F., Makishima, K., Marscher, A., McEnery, J., Mc Hasrady, I.M., Meyer, D.I., Moore, E.M., Robson, E.I., Rose, H.J., Schubnell, M.S., Sembroski, G., Stevens, J.A., Takahashi, T., Tashiro, M., Weekes, T.C., Wilson, C., and Zweerink, J. 1995, *ApJL*, 449, L99. Multi-wavelength Observations of Mkn 421 during a TeV/X-ray Flare.

Schubnell, M.S., Akerlof, C.W., Biller, S.D., Buckley, J.H., Carter-Lewis, D.A., Cawley, M.F., Chantell, M., Connaughton, V., Fegan, D.J., Fennell, S., Gaidos, J.A., Hillas, A.M., Kerrick, A.D., Lamb, R.C., Meyer, D.I., Mohanty, G., Rose, H.J., Rovero, A.C., Sembroski, G., Weekes, T.C., Wilson, C. and Zweerink, J., 1995, *ApJ*, 460, 644. Very High Energy Gamma-ray Emission from the Blazar Markarian

Buckley, J. H., Akerlof, C. W., Biller, S. D., Carter-Lewis, D. A., Cawley, M. F., Catanese, M., Connaughton, V., Fegan, D. J., Finley, J. P., Gaidos, J. A., Hillas, A. M., Kartje, J. F., Konigl, A., Krennrich, F., Lamb, R.C., Lessard, R., Mattox, J. R., McEnery, J., Mohanty, G., Quinn, J., Rodgers, A. J., Rose, H. J., Schubnell, M. S., Sembroski, G., Smith, P. S., Weekes, T. C., Wilson, C. and Zweerink, J., Gamma-ray Variability of the BL Lacertae Object Markarian 421 1996, *ApJL* 472, L9 (1996). (also Buckley et al., IAU Circular #6178 (1995)).

Connaughton, V., Akerlof, C. W., Barthelmy, S., Biller, S. D., Boyle, P., Buckley, J. H., Carter-Lewis, D. A., Catanese, M., Cawley, M. F., Cline, T., Fegan, D. J., Finley, J., Fishman, G. J., Gaidos, J. A., Gehrels, N., Hillas, A. M., Kouveliotou, C., Lamb, R. C., Lessard, R., McEnery, J., Meegan, C., Mohanty, G., Porter, N. A., Quinn, J., Rose, H. J., Rovero, A.C., Samuelson, F., Schubnell, M. S., Sembroski, G., Srinivasan, R., Weekes, T. C., Wilson, C. and Zweerink, J. "A Search for TeV Counterparts to BATSE Gamma-ray Bursts", *ApJ* (1997) 479, 859.

Urban, M., Chantell, M., Fleury, P., Harris, K., Gaidos, J.A., Kerrick, A., Pare, E., Punch, M., Sarazin, X., Vacanti, G. Weekes, T.C., and Wilson, C., The Use of a UV Camera in the Atmospheric Cherenkov Technique. N.I.M. A368, 503 (1996).

Weekes, T. C., Akerlof, C., Biller, S., Bussons, J., Buckley, J. H., Catanese, M., Carter-Lewis, D. A., Cawley, M. F., Connaughton, V., Fegan, D. J., Finley, J., Gaidos, J., Hillas, A. M., Lamb, R. C., Krennrich, F., Lessard, R., McEnery, J., Meyer, D. I., Mohanty, G., Quinn, J., Rodgers, A., Rose, H. J., Schubnell, M. S., Sembroski, G., Wilson, C., Zweerink, J. "Observations of Gamma-ray Sources with  $E > 300$  GeV", *Proceedings of Compton Gamma Ray Observatory Symposium*, Munich, June 1995, *Astr. and Astrophys. Suppl.* (1996) 120, 603.

Chantell, M., Akerlof, C. W., Badran, H., Buckley, J. H., Carter-Lewis, D. A., Cawley, M. F., Connaughton, V., Fegan, D. J., Fleury, P., Gaidos, J. A., Hillas, A. M., Lamb, R. C., Pare, E., Rose, H. J., Rovero, A. C., Sarazin, X., Sembroski, G., Schubnell, M. S., Urban, M., Weekes, T. C. and Wilson, C. "Gamma-ray Observations in Moonlight with the Whipple Atmospheric Cherenkov Hybrid Camera", *Astroparticle Physics* (1997) 6, 205.

Connaughton, V., Akerlof, C.W., Biller, S.D., Buckley, J.H., Carter-Lewis, D.A., Catanese, M., Cawley, M.F., Fegan, D.J., Gaidos, J.A., Hillas, A.M., Lamb, R.C., Lessard, R., McEnery, J., Mohanty, G., Porter, N.A., Quinn, J., Rose, H.J., Rovero, A.C., Samuelson, F., Schubnell, M.S., Sembroski, G., Srinivasan, R., Weekes, T.C., Wilson, C. and Zweerink, J., 1996, *Astroparticle Physics* (submitted) A Search for TeV Gamma-ray Bursts on a 1-second Time-scale.

Catanese, M., Akerlof, C.W., Biller, S.D., Boyle, P.J., Buckley, J.H., Carter-Lewis, D.A., Cawley, M.F., Connaughton, V., Dingus, B.L., Fegan, D.J., Finley, J.P., Gaidos, J.A., Gear, W.K., Hartman, R.C., Hillas, A.M., Krennrich, F., Lamb, R.C., Lessard, R., Lin, Y.C., McEnery, J., Marscher, A.P., Mohanty, G., Mukherjee, R., Quinn, J., Robson, E.I., Rodgers, A.J., Rose, H.J., Samuelson, F., Schubnell, M.S., Sembroski, G., Stevens, J.A., Terasranta, H., Thompson, D.J., Weekes, T.C., Wilson, C.L. and Zweerink, J., "Detection of Gamma Rays with  $E > 100$  MeV from BL Lacertae", *ApJ* 480, 562 (1997).

Gaidos, J. A., Akerlof, C. W., Biller, S. D., Boyle, P. J., Breslin, A. C., Buckley, J. H., Carter-Lewis, D. A., Catanese, M., Cawley, M. F., Fegan, D. J., Finley, J. P., Hillas, A. M., Krennrich, F., Lamb, R. C., Lessard, R., McEnery, J., Mohanty, G., Moriarty, P., Quinn, J., Rodgers, A., Rose, H. J., Samuelson, F., Schubnell, M. S., Sembroski, G., Srinivasan, R., Weekes, T. C., Wilson, C. L. and Zweerink, J. "Very Rapid and Energetic Bursts of TeV Photons from the Active Galaxy Markarian 421", 1996, *Nature* 383, 319.

Krennrich, F., Akerlof, C., Biller, S., Buckley, J. H., Catanese, M., Carter-Lewis, D. A., Cawley, M. F., Chantell, M., Connaughton, V., Fegan, D. J., Finley, J., Gaidos, J., Hillas, A. M., Kertzman, M., Lamb, R. C., Lessard, R., McEnery, J., Meyer, D., Mohanty, G., Quinn, J., Rose, H. J., Schubnell, M. S., Sembroski, G., Srinivasan, R., Weekes, T. C., Wilson, C., Zweerink, J. "Observations of Markarian 421 at Large Zenith Angles", 1996, *ApJ*, 481, 758.

Srinivasan, R., Buckley, J. H., Carter-Lewis, D. A., Catanese, M., Cawley, M. F., Colombo, E., Fegan, D. J., Finley, J. P., Gaidos, J. A., Hillas, A. M., Krennrich, F., Lamb, R. C., Lessard, R., McEnery, J., Moriarty, P., Quinn, J., Rodgers, A., Rose, H. J., Sembroski, G., Weekes, T. C., Wilson, C. L. "Very High Energy Observations of PSR B1951+32", *ApJ*, (1997) 489, 170.

Hillas, A. M., Akerlof, C.W., Biller, S., Buckley, J.H., Burdett, A.M., Carter-Lewis, D. A., Catanese, M., Cawley, M. F., Fegan, D. J., Finley, J. P., Gaidos, J. A., Krennrich, F., Lamb, R. C., Lang, M.J., Mohanty, G., Punch, M., Reynolds, P.T., Rodgers, A. J., Rose, H. J., Rovero, A., Schubnell, M.S., Sembroski, G. H., Vacanti, G., Weekes, T. C., West, M., and Zweerink, J. "Spectrum Of TeV Gamma Rays from the Crab Nebula" *ApJ*, (submitted) (1997).

Catanese, M., Bradbury, S. M., Breslin, A. C., Buckley, J.H., Carter-Lewis, D. A., Cawley, M. F., Dermer, C. D., Fegan, D. J., Finley, J. P., Gaidos, J. A., Hillas, A. M., Johnson, W. N., Krennrich, F., Lamb, R. C., Lessard, R., Macomb, D. J., McEnery, J. E., Mohanty, G., Quinn, J., Rodgers, A. J., Rose, H. J., Samuelson, F. W., Sembroski, G. H., Srinivasan, R., Weekes, T. C., and Zweerink, J. "Multiwavelength Observations of a Flare from Markarian 501" *ApJL* (1997) 487, L143.

Buckley, J. H., Akerlof, C. W., Carter-Lewis, D. A., Catanese, M., Cawley, M. F., Connaughton, V., Fegan, D. J., Finley, J. P., Gaidos, J. A., Hillas, A. M., Krennrich, F., Lamb, R. C., Lessard, R., McEnery, J. E., Mohanty, G., Quinn, J., Rodgers, A. J., Rose, H. J., Rovero, A. C., Schubnell, M. S., Sembroski, G. H., Srinivasan, R., Weekes, T. C., and Zweerink, J. "Constraints on cosmic-ray origin from TeV gamma-ray observations of supernova remnants" *Astron. Astrophys.* (1997) (in press)

Buckley, J. H., Akerlof, C. W., Biller, S., Boyle, P. J., Breslin, A. C., Carter-Lewis, D. A., Catanese, M., Cawley, M. F., Connaughton, V., Fegan, D. J., Finley, J. P., Gaidos, J. A., Gordo, B. J., Hillas, A. M., Krennrich, F., Lamb, R. C., Lessard, R., Masterson, C., McEnery, J. E., Mohanty, G., Quinn, J., Rodgers, A. J., Rose, H. J., Rovero, A. C., Samuelson, F., Schubnell, M. S., Sembroski, G. H., Srinivasan, R., Weekes, T. C., Wilson, C., and Zweerink, J. "Gamma-ray Variability of BL Lacs at  $E > 300$  GeV" *Adv. in Space. Res.* (1997) in press.

Mohanty, G., Hillas, A.M., West, M., Biller, S., Carter-Lewis, D.A., Lamb, R.C., Zweerink, J., Fegan, D.J., Weekes, T.C. "Measurement of TeV Gamma-ray Spectra with the Cherenkov Imaging Technique" *Astroparticle Physics* (1997) (submitted).

Zweerink, J., Akerlof, C., Biller, S., Boyle, P., Buckley, J.H., Burdett, A.D., Bussons Gordo, J., Carter-Lewis, D. A., Catanese, M., Cawley, M. F., Fegan, D.J., Finley, J., Gaidos, J., Hillas, A. M., Krennrich, F., Lamb, R.C., Lessard, R., McEnery, J., Mohanty, G., Quinn, J., Rodgers, A.J., Rose, H.J., Samuelson, F.W., Schubnell, M.S., Sembroski, G., Srinivasan, R., Weekes, T. C., Wilson, C., "The TeV Gamma-Ray Spectrum of Markarian 421 during an Intense Flare", *ApJL*, 490, L141 (1997).

Akerlof, C., Biller, S., Boyle, J., Buckley, J. H., Carter-Lewis, D. A., Catanese, M., Cawley, M. F., Connaughton, V., Fegan, D. J., Finley, J., Gaidos, J., Hillas, A. M., Krennrich, F., Lamb, R. C., Lessard, R., McEnery, J., Mohanty, G., Porter, N.A., Quinn, J., Rodgers, A., Rose, H. J., Samuelson, F., Schubnell, M. S., Sembroski, G., Srinivasan, R., Weekes, T. C., Zweerink, J., "A Search for Correlations of TeV and PeV gamma-rays with Ultra-High Energy Cosmic Rays", *ApJ* (submitted) 1997.

Biller, S., Buckley, J.H., Burdett, A.D., Bussons Gordo, J., Carter-Lewis, D. A., Fegan, D.J., Gaidos, J., Hillas, A. M., Krennrich, F., Lamb, R.C., Lessard, R., McEnery, J., Mohanty, G., Quinn, J., Rodgers, A.J., Rose, H.J., Samuelson, F.W., Schubnell, M.S., Sembroski, G., Skelton, P., Weekes, T. C., Zweerink, J., "New Limits to the IR Background: Bounds on Radiative Neutrino Decay and on VMO Contributions to the Dark Matter Problem", *ApJ*, submitted, 1997.

Lamb, R.C., and Macomb, D.J., *ApJ* 488, 872 1997.

Catanese, M., Akerlof, C.W., Badran, H.M., Biller, S.D., Bond, I.H., Boyle, P.J.,

Bradbury, S.M., Buckley, J.H., Burdett, A.M., Bussons Gordo, J., Carter-Lewis, D.A., Cawley, M.F., Connaughton, V., Fegan, D.J., Finley, J.P., Gaidos, J.A., Hall, T., Hillas, A.M., Krennrich, F., Lamb, R.C., Lessard, R., Masterson, C., McEnery, J.E., Mohanty, G., Quinn, J., Rodgers, A.J., Rose, H. J., Samuelson, F.W., Schubnell, M.S., Sembroski, G.H., Srinivasan, R., Weekes, T.C., Wilson, C.W., and Zweerink, J., "Discovery of  $> 350$  GeV Gamma Rays from the Bl Lac Object 1E2344+514", ApJ, (submitted), 1997.

Krennrich, F., Akerlof, Buckley, J. H., Bussons Gordo, J., Carter-Lewis, D. A., Cawley, M. F., Catanese, M., Connaughton, V., Fegan, D. J., Finley, J. P., Gaidos, J. A., Harris, K. H., Hillas, A. M., Lamb, R. C., Lang, M. J., Mohanty, G., Quinn, J., Rodgers, A. J., Rose, H. J., Rovero, A. C., Schubnell, M. S., Sembroski, G. H., Weekes, T. C., Wilson, C. W., "Stereoscopic Observations of Gamma Rays at the Whipple Observatory", Astroparticle Physics, in press, 1997.